ARCHIVES OF ACOUSTICS
36, 4, 713–726 (2011)
DOI: 10.2478/v10168-011-0048-2

Vibration Modes of the Cello Tailpiece(*)

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(*received January 16, 2011; accepted September 20, 2011*)

The application of modern scientific methods and measuring techniques can extend the empirical knowledge used for centuries by violinmakers for making and adjusting the sound of violins, violas, and cellos.

Accessories such as strings and tailpieces have been studied recently with respect to style and historical coherence, after having been somehow neglected by researchers in the past. These fittings have played an important part in the history of these instruments, but have largely disappeared as they have been modernised. However, the mechanics of these accessories contribute significantly to sound production in ways that have changed over time with different musical aesthetics and in different technical contexts. There is a need to further elucidate the function and musical contribution of strings and tailpieces.

With this research we are trying to understand the modifications of the cello's sound as a consequence of tailpiece characteristics (shape of the tailpiece and types of attachments). Modal analysis was used to first investigate the vibration modes of the tailpiece when mounted on a non-reactive rig and then when mounted on a real cello where it can interact with the modes of the instrument's corpus. A preliminary study of the effect of the tailpiece cord length will be presented.

Keywords: violincello, cello, modal analysis, tailpiece, accessories.

(*) This article was originally presented at Vienna Talk (Fouilhé *et al.*, 2010) and was chosen for a journal publication.

1. Introduction

1.1. History

Since the middle ages, the strings of bowed instruments may have been attached to a pin at the bottom of the sound box (violins, violas, kits, sarangis) or attached to a piece of leather, material, or gut string. Iconography shows that in the Renaissance, for violins and viols, a piece of wood cut into an intricate shape at first, then simplified in a flat dove tail shape, was used. Tailpieces from the 17th, 18th, 19th, and 20th century for the viol family, as well as for the violin family, are kept in the Music Museum in Paris, and they show the changes that have taken place over the centuries. The top surface of the tailpiece became more rounded at the end of the 18th century, and that increases the angle of the lateral strings on the bridge, which means a stronger force applied vertically onto the sounding box from those strings. This shows a want of a bigger sound and a balance between the middle, the treble, and the bass strings. A little fret was also added, in order to have a definite "tuning" of the afterlength of the string, whereas before, the strings didn't have a definite stop at the tailpiece end. Violoncellos, of modern size, were being made before 1700, soon after the invention of overspinning strings with metal, and progressively replaced the old, larger "Basse de violon" which had much thicker gut strings. Today, when set up as a modern cello, it has a tailpiece that can be made of hard wood, metal, or plastic, and, most of the time, it has four adjusters to hold and fine tune four thin heavily wound metal strings. Modifications in the material, shape, weight of the tailpieces usually followed the evolution of strings.

The attachment cord used to be in gut, it was tried in rigid metal as well, and in the 20th century piano strings have been used, as well as nylon or Kevlar.

1.2. State of the art

In 1993, while working on violin modes, Hutchins (1993) mentioned the possibility of tuning the tailpiece to the frequency of modes in the violin itself. A study of the vibrating modes of violin tailpieces was then carried out and published by Bruce Stough (1996), and he explored all the resonances below 1500 Hz, in which the violin tailpiece moves as a rigid body. He defined 6 degrees of freedom: 1. Torsion around a lengthwise axis (revolution); 2. Rocking around a transverse line; 3. Rotation around a vertical axis; 4. Up and down movement; 5. Left to right movement; 6. Forward to backward movement. For the violin tailpiece, Stough found 5 rigid body modes below 1500 Hz: 1. Swing bass side, 2. Swing treble side, 3. Swing under, 4. Rotation around vertical axis, 5. Rotation round horizontal axis. In 2002, Woodhouse in his work (2002) notes specifically that he found 3 typical modes under the fundamental note of the violin: G (196 Hz) and two others in the bracket 300 to 800 Hz. The frequencies of the modes depend on the mass and on the length of the tailgut.

2. Material and methods

Our work was performed partly on a real cello and partly on a dead rig in order to eliminate the cello's influences and evaluate the tailpiece behaviour. To perform the modal analysis, we used the GS Software suite, which was developed by George Stoppani himself. The software suite is composed of several subprograms: "Mode shape" enables setting up a shape and defining where the tapping points are chosen on the object, "Acquisition" is the program that calculates the ratio of the accelerometer response to the hammer excitation force, acquires data and stores them separately, "FRF overlay" allows to superpose the results and compare them, "Modefit" allows the mode fitting, and "Mode shape" again allows to measure displacement and acceleration of each point to the equivalent point on the drawn outline of the object in order to reproduce the movement virtually. The representation in two dimensions of the 3 different planes allows us to analyse the movement.

In earlier experiments (Fouilhe *et al.*, 2009), we achieved a modal analysis of a cello tailpiece mounted on a Stoppani's manufactured cello in playing conditions. For the present paper, the study was then followed by the construction, in Eric Fouilhé's workshop in France, of a dead rig, of the dimensions of the cello string length, body length, and bridge dimension in order to isolate the behaviour of the tailpiece from the vibrations of the instrument, and to eliminate as much as possible the coupling between the strings/tailpiece group and the cello.

The study consisted in establishing the different modes on a specimen tailpiece, afterwards, evaluating differences of changes of mass and of mass distribution by placing magnets on the tailpiece, or in changing the tailcord length. The same changes were then made on a cello which was then played by a musician, a recording was made, and his comments noted for later analysis.

We will present here the first part of our work on the determination of the cello tailpiece mode shapes.

3. Acquisitions

3.1. Set up of the experiment

The dead rig is a rigid cello set up, mounted on an I-beam on which a blank bridge and an endpin are fixed. The tailpiece is fixed in the usual manner with a tail string. For the standard test, we have a string length of 69.5 cm. The string angle and the tuning CGDA stay the same for each experiment. There is neither vibrating body nor fingerboard. The bridge is reinforced in order to keep it still. The same tailpiece was measured and the strings are muted with a felt band.

The stand holds the chain [string length + bridge + afterlength of the string + tailpiece + tailcord + saddle + endpin] identical to that which is mounted on a real violoncello (see Fig. 1). Particular attention was given to the steady fixations of the bridge and saddle, which are the contact points to the rig.

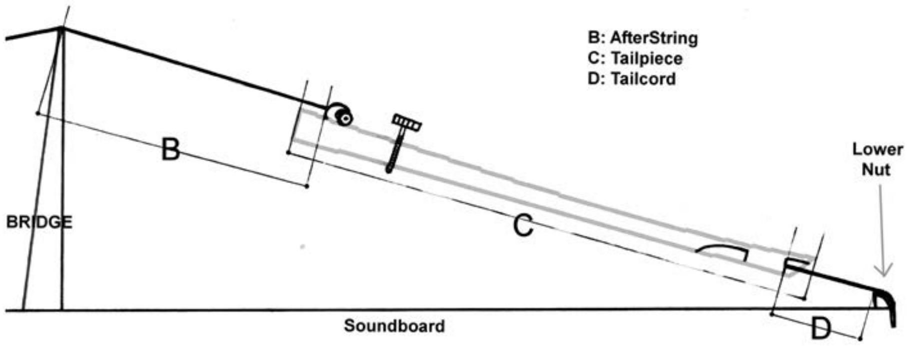

Fig. 1. The chain [bridge + afterlength of the string + tailpiece + tailcord + saddle].

The system was tested for its mobility, particularly the lower saddle (on which the tailpiece string lies) and the bridge, in the frequency range of the three modes 1, 2, and 4, which are the most significant in amplitude. The mobility of the bridge was then found to be less than 5 of the tailpiece mobility in the three planes. The lower saddle, on which the tailpiece string lies, can fetch 2% in the vertical plane, normal to the cello table, and 7 in lateral mobility left to right of the instrument. We therefore consider the dead rig as sufficiently still to study its vibration without significant influence on coupling of the holding device.

The points where the measurements were to be taken have been carefully chosen according to dimensions of the tailpiece and the wavelengths of the frequencies considered.

3.2. Measurements

Figure 2 shows the taping grid with upper and lateral views. The points shown in the grid were hit, and the positions of the accelerometer for the acquisition in 3 axes are shown in red. In Fig. 3 the set up can be seen. Each point is hammered ten times, and the double bounce taps are automatically detected and suppressed. Two other measurement sets of 42 points were acquired after moving the accelerometer in each of the two other positions (38 for lengthwise motion and 26 for lateral motion) in order to highlight the three planes directions of vibration. The acquisition rate was chosen at 44.1 kHz, in 24 bits for 65536 samples. The hits were produced by a PCB 4.8 g hammer, model 086E80, and

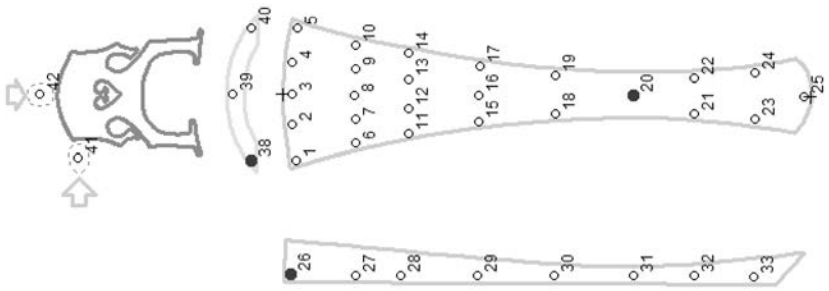

Fig. 2. Selected points to hit with the hammer and accelerometer positions (red points). Points 1–25, 34–35: vertical taping on tailpiece and saddle; points 26–33: lateral taping on tailpiece; points 36–40: longitudinal taping on tailpiece and saddle; points 41, 42: lateral and vertical taping on the bridge.

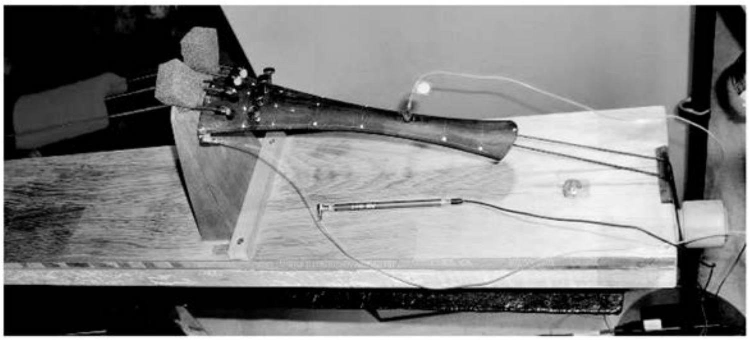

Fig. 3. Dead rig, reference tailpiece marked, accelerometer in place, and hammer.

the vibrations recorded by a PCB uni-axial 0.6 g piezoelectric accelerometer, model 352A21.

Several other sets of measurements with different tailpieces of different materials were taken in order to give some variability of the frequencies.

Finally, tests have been made in adding mass to the reference tailpiece, and in changing the tail cord length, to study the variation of frequency of the modes. Each time, a new set of measurement was taken.

3.3. Analysis

Once the acquisition completed, the data was observed with the FRF Overlay utility (see Fig. 4) highlighting the main modes. We made various averages of the different groups (for the different accelerometer locations).

For the selected modes we used the ModeFit utility of GS Software (see Fig. 5) in order to mathematically fit the FRF curves to find the modes with Rational Fraction Polynomial calculations. It is sensible to choose a frequency resolution that is fine enough to show separate peaks.

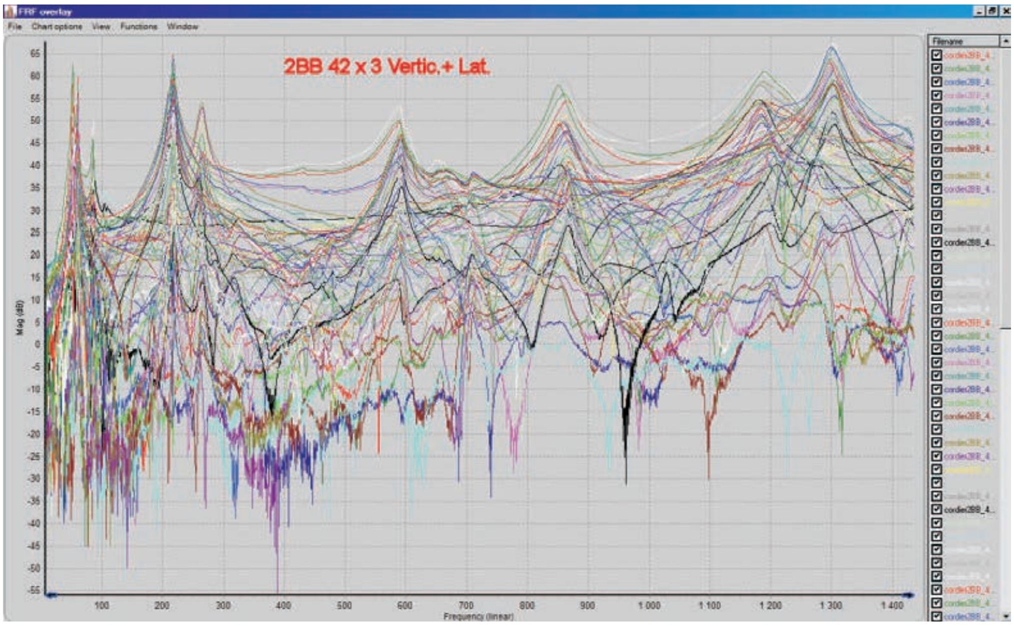

Fig. 4. Data observed by FRF Overlay utility of GS Software.

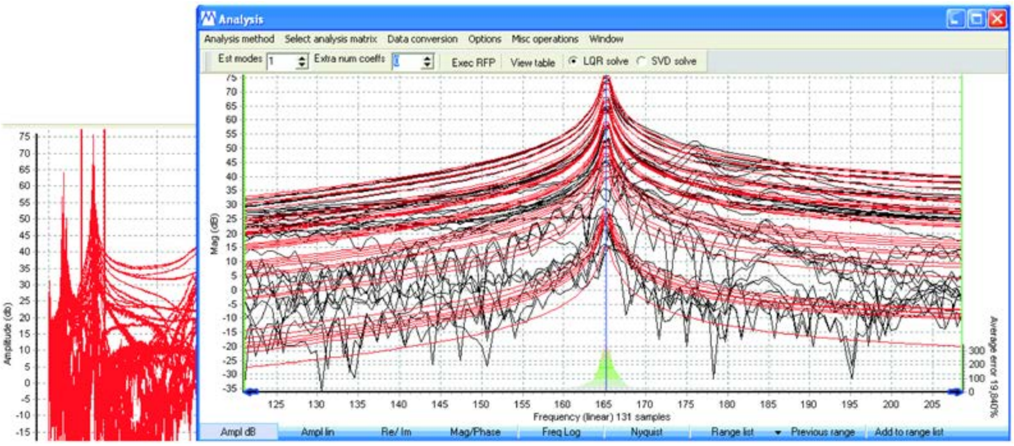

Fig. 5. Using the ModeFit utility of GS Software.

A time window long enough to contain the decay and a sample rate high enough to avoid aliasing of frequencies above the Nyquist frequency were chosen. With a window of 65536 and a 44.1 kHz acquisition rate, we get a frequency resolution of 0.67 Hz.

The fitted data of each mode were then used in the GS Mode Shape application in order to attribute the measurements to the 3 planes of our drawing, to simulate the tailpiece behaviour for each single mode.

4. Results

The length of the tailcord on the dead rig for this test reference was 22 mm. It was chosen to correspond to the optimum sound perception of a real cello, fitted with the same accessories. The normal length of the tailcord on a cello is set by the maker between 10 and 45 mm.

A total of 9 modes were found (see Fig. 6).

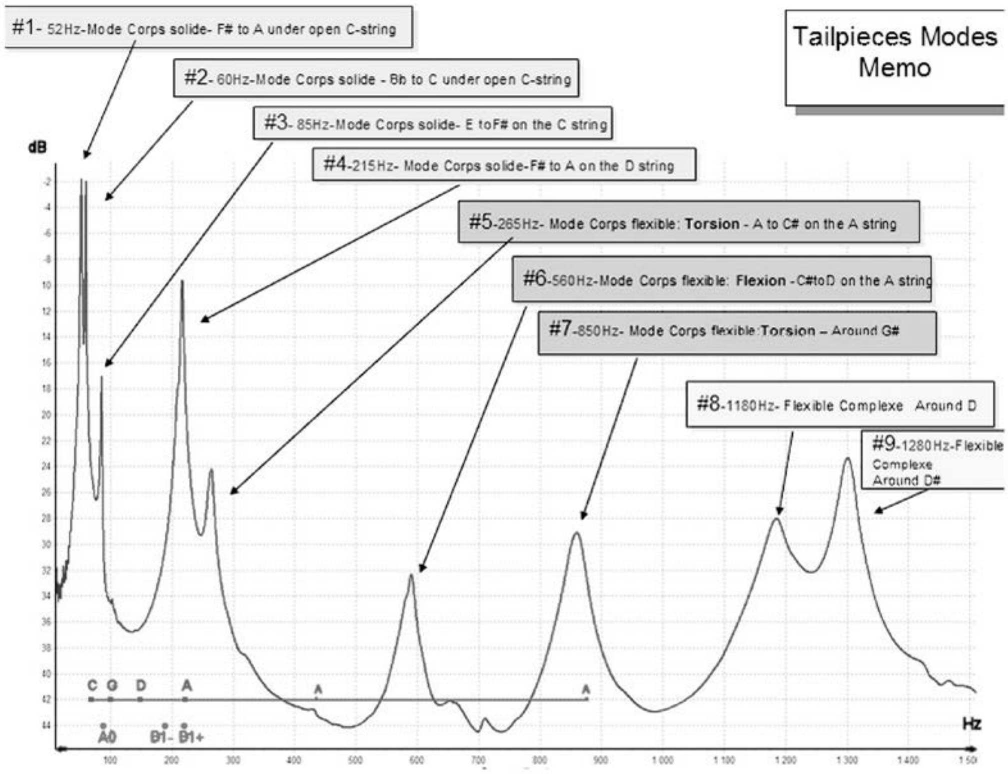

Fig. 6. Modes of cello tailpiece, strings, and range frequency of the body cello modes. Amplitude (dB)/Frequency (Hz).

The first four modes of the cello tailpiece are rigid body motion modes, the two lowest being found below the lowest C string, while mode 3 is a third or a fourth above, near the Helmholtz A0 mode of the cello.

Then, modes 5, 6, and 7 are flexible modes, implying that the thickness and material of the tailpiece is involved. Their frequencies are within the range of the instrument, the last one being at the top G# near the highest note that can be played on the A string.

Modes 8 and 9 are more complex, involving flexion and motion, and we record them for reference.

4.1. Mode 1
(F# to A under open string C2 at 65.4 Hz)

It is a rigid body motion with predominant lateral swing and does not appear on little width vertical tapping.

Looking like a windscreen wiper the movement (see Fig. 7) is nearly on a plane. The amplitude is large, second after mode 2. When the tailcord was crossed over the saddle, the rotation of the tailpiece could be bigger, and this mode went down 9 Hz (20%), which is significant with the frequency resolution of 0.67 Hz (see Subsec. 3.3). With shortening the tailpiece chord, first mode 1 goes down, then it goes up again.

Fig. 7. Mode 1.

4.2. Mode 2
(Bb to C2 at 65.4 Hz)

It is also a full body mode with a prominent vertical motion; it looks a bit like a large bat motion, displacing air (see Fig. 8). This mode has the strongest amplitude; the peaks are narrow, suggesting a smaller damping than for mode 1.

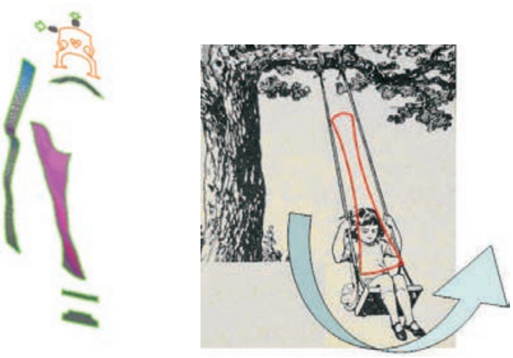

Fig. 8. Mode 2.

Crossing the tailcord on the saddle does not affect the frequency. Adding a 30 g mass at 2/3 towards the bottom end of the tailpiece lowers the frequency by 7 Hz. Adding a 30 g mass at 1/4 of the upper end of the tailpiece lowers it by 11 Hz. Shortening the tailcord diminishes the frequency and increases the amplitude. When it is at 4 cm from the bridge the motion is maximum. When the tailpiece is nearer the saddle, at a normal distance used today, the mode is still lower in frequency.

4.3. Mode 3
(E to F#, on the C string)

It is not a particularly homogeneous mode. Laterally, the strong lever near the saddle resembles the lateral motion of mode 1 (see Fig. 9). Like mode 1, it is a rigid body mode, with a lateral pre-eminence, not seen or very little seen on vertical tapping. It looks like a windscreen wiper movement with a stronger diagonal tendency, the upper treble corner plunging. The amplitude is about half of that of mode 1. Modes 1 and 3 seem attached, going up and down in frequency together with the change of the tailcord length or when crossing the tailcord. Mode 3 is near the A0 Helmholtz mode of the cello.

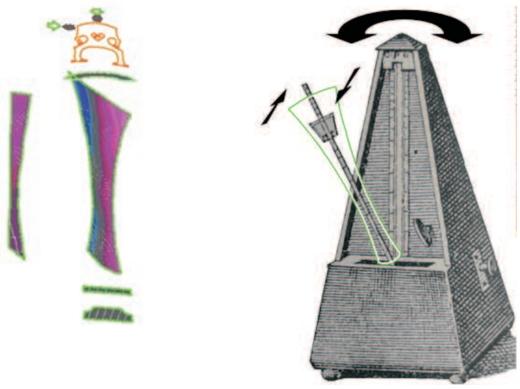

Fig. 9. Mode 3.

4.4. Mode 4
(F# to A on the D string)

It is a full body vertical mode with a strong seesaw with an axis at the upper third or quarter of the tailpiece length, combined with a small torsion of the bottom of the tail (see Fig. 10). Laterally, there is a small flexing with seesaw or torsion. It is a powerful motion with maximum amplitude near to that of modes 1 and 2. It is always associated with mode 5's lateral mode (see below). Mode 4 is very near to the B1+ mode of the cello.

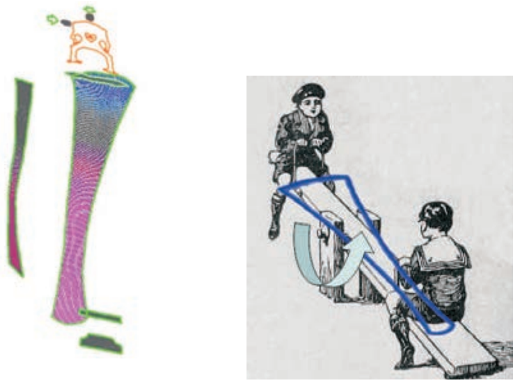

Fig. 10. Mode 4.

4.5. Mode 5
(A to C# on the A string)

This is the first mode of torsion (similar to mode 1 of a free rectangular plate) with crossed nodal lines and the 4 corners going up and down by diagonal pairs (see Fig. 11). Vertically, there is a torsion with a vertical axis normal to the plate at points 12–13. Laterally, it has a strong rocking axis at the same place, but it is a laterally and lengthwise excited mode. Although no RMS is visible in the vertical motion, GS Modefit detected one vertical mode.

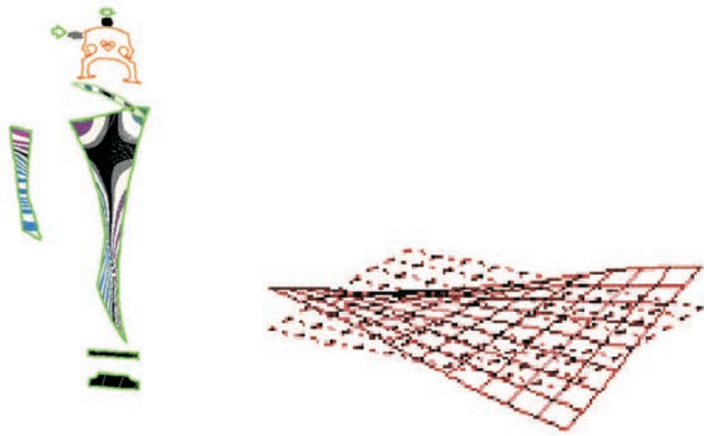

Fig. 11. Mode 5.

This mode has a smaller amplitude than mode 4. It is attached to mode 4 (shortening the tailcord) and is very affected by the change in the string tension. In the free-free mode, its frequency goes up from 265 to 937 Hz (+250%).

4.6. Mode 6
(C# to D)

Vertically, very sensitive, mode 6 is also a flexion mode with a strong bending and one antinode: it looks like a first mode of a beam (see Fig. 12). Laterally, the flexing is negligible to feeble also with one antinode. The amplitude is small as compared with other modes. The peak is often not clear and possibly there are several peaks superimposed.

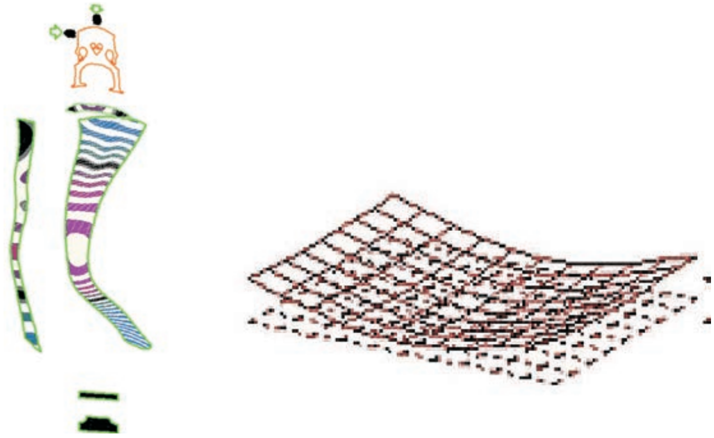

Fig. 12. Mode 6.

When crossing the tailcord on the saddle, the rotation is suppler, so the peak is bigger and more defined, and the frequency lowers by 70 Hz.

When adding weight 30 g at 2/3 towards the bottom end of the tailpiece, mode 6 seems to be cut in two: one peak lowers by 155 Hz, the other goes up by 60 Hz, both with an increase of amplitude.

When adding weight 30 g at 1/4 of the upper end of the tailpiece only the upper peak appears. These strong variations are surprising because the weights were added not far from nodal lines.

With shortening the tailcord from 5.5 to 1.1 cm, mode 6 increases in frequency +73 Hz, with two exceptions. Amplitude is halved and the shape of the peak remains unchanged. These modifications resemble modes 4 and 5.

When the strings are loose, the frequency lowers to 100 Hz (−17%), so it takes the place of the first mode of torsion.

4.7. Mode 7
(from 827.24 to 857.15 Hz, around G#)

Vertically, it is a medium to strong torsion.

Laterally, a strong seesaw is present centred at points 12–13 (see Fig. 13).

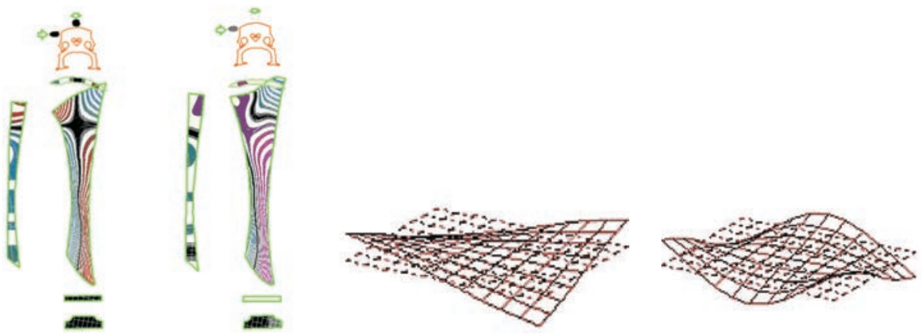

Fig. 13. Mode 7.

Similar to mode 2 of torsion of a plate with a strong lateral seesaw. Its axis is 2/3 from the top, one side curls up while the other one curls down, opposite corners having opposite directions. The amplitude is larger than that for mode 6, the peak is very pointed and neat. The strong peak appears with lateral excitation; it does not exist vertically.

When the tailcord is crossed on the saddle, the peak is attenuated, but the frequency does not move.

When adding a mass of 30 g there is no result because only vertical tapping was done.

With shortening the tailcord the frequency increases by 29 Hz with a slight increase of the amplitude.

4.8. Mode 8
(frequency from 1150 to 1189.65 Hz, around D)

Vertically, this mode is affected by a lateral excitation; there is a swinging from left to right like in mode 1 and a torsion with two nodes. Laterally, there is a strong flexing and bending with one antinode (see Fig. 14).

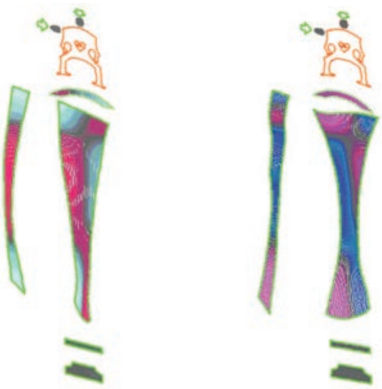

Fig. 14. Mode 8.

4.9. Mode 9
(frequency from 1263 to 1332.62 Hz, around D#)

Vertically, there is a strong twist or a flexing. Laterally, there is a strong bending with one antinode, otherwise there is a complex flexing (see Fig. 15). Dominance of the vertical motion, no lateral excitation is visible.

Fig. 15. Mode 9.

5. Conclusions

We succeeded in identifying 9 modes of a reference cello tailpiece under tension on a dead rig: four full body motions, two torsion modes, one bending mode, and two complex modes above the cello's range.

The two first modes are below the lowest note of the cello.

The third mode is near the A0 Helmholtz mode of the cello, while mode 4 is still below the A string, but very near the B1+ mode of the cello.

Changing the tension of the strings influences the first three modes, lowering them by 6%. Adding an extra mass (30 g) on the tailpiece lowers these modes from 9 to 29% depending where the mass is placed.

Modes 1 and 3 seem attached, going up and down in frequency together with the change of the tail cord length or when crossing the tail cord.

The definitions of the modes will be pursued to study their variations to understand the influence of geometry, material, and fixation once on the instrument. Finally, the perception of the musician will be studied in order to find out how these different set ups and modes influence the playing feel.

Acknowledgments

We would like to thank George Stoppani for the permission to use freely GS Software suite and the COST action IE0601 "WoodCultHer" for financing three Short Term Scientific Missions at George Stoppani's workshop in Manchester.

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